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Ice-margin seismic stratigraphy of the central Scotian Slope, eastern Canada[1]

David J.W. Piper, David C. Mosher, and Simon Newton

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Abstract: Seismic reflection profiles along the upper Scotian Slope show a series of stacked till tongues interpreted to represent Pleistocene glacial maximum conditions. The deepest till unit immediately underlies regional reflector I, which marks a change from prodeltaic to proglacial depositional style on the continental slope. Regional unconformities appear to follow deglaciation. Thick glacial-plume deposits are characteristic of deglacial periods and associated with till tongues. They are most prominent beneath regional reflector I, believed to be derived from the Gulf of St. Lawrence, correlated with marine isotope stage 12 in a long pelagic core from the J-Anomaly ridge. This chronological tie allows consistent interpretation of ages of till tongues and proglacial facies. The deepest till tongue formed at the end of marine isotopic stage 10. Till deposits in marine isotopic stage 12 are recognized only on the outermost shelf and did not extend to the slope.

Résumé : Des profils de sismique réflexion le long de la partie supérieure du talus Néo-Écossais révèlent la présence d'une série de langues de till empilées qui indiqueraient des conditions de pléniglaciaire pléistocène. L'unité de till la plus profonde se trouve juste sous le réflecteur régional I qui marque un changement du style de sédimentation de prodeltaïque à proglaciaire sur le talus continental. Les discordances régionales semblent suivre la déglaciation. Des dépôts glaciaires épais en forme de panache sont caractéristiques des périodes de déglaciation et associés à des langues de till. Ils apparaissent avec plus de netteté sous le réflecteur régional I, qui provient vraisemblablement du golfe du Saint-Laurent et est mis en corrélation avec le stade isotopique marin 12 dans une longue carotte pélagique extraite dans la dorsale de l'anomalie J. Ce lien chronologique permet une interprétation cohérente des âges des langues de till et du faciès proglaciaire. La plus profonde langue de till s'est formée à la fin du stade isotopique marin 10. Des dépôts de till du stade isotopique 12 ne sont reconnus que sur la partie la plus externe de la plate-forme et ne se prolongent pas jusqu'au talus.

[1] Contribution to PERD

INTRODUCTION

Glacial ice reached the edge of the Scotian Shelf several times during the middle to late Quaternary (Mosher et al., 1989; Stea et al., 1998). At that time, sedimentation on the continental slope was dominated by deposition of glaciomarine muds with ice-rafted detritus (Hill, 1984; Mosher et al., 1994), likely a result of advance and retreat of these shelf-crossing ice sheets.

Several lines of evidence indicate the former presence of ice on the outer shelf. 1) The presence, on the outer shelf, of acoustically incoherent sediment bodies that resemble glacial till identified from sediment samples, and the morphology of morainal ridges elsewhere on the shelf (King and Fader, 1986). Similar stacked acoustic units on the Norwegian Shelf have been demonstrated to be till from numerous boreholes (King et al., 1991). 2) The acoustic continuity of these outer shelf bodies into 'till tongues' that extend to water depths of 500 m on the upper slope. Whether these till tongues represent deposition from grounded ice or some form of proglacial ice-contact debris flow is debated (Stravers and Powell, 1997; Gipp, 2000). 3) The presence of widespread glacial-plume sediments and of ice-rafted detritus that petrography shows emanated from multiple sources along the ice margin (Piper and deWolfe, in press).

In this study, we use seismic reflection profiles from an area immediately east of Dawson Canyon (Fig. 1) to better understand ice-margin processes on the upper slope. We apply a chronostratigraphy based on correlation of major glacial advances with the global ice-volume record preserved in oxygen isotopes of foraminifera. Such interpretations can be used to infer the character of the upper few hundred metres of sediment on the Scotian Slope.

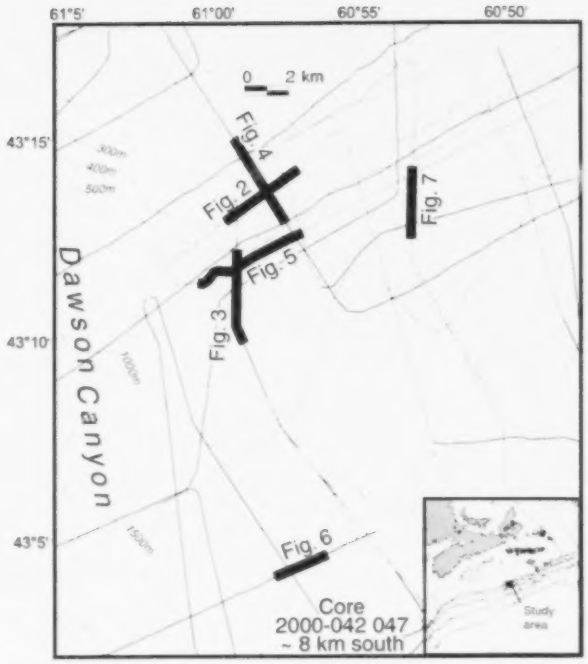

Figure 1. *Generalized bathymetry of the study area showing locations of seismic reflection profiles. Illustrated profiles are shown as bold lines. Inset shows regional setting on the Scotian margin.*

GEOLOGICAL SETTING

Morphology of the study area

The study area is immediately east of Dawson Canyon (Fig. 1). The upper slope is regionally planar and heavily pocked by iceberg pits, scours, and possible gas pockmarks (Pickrill et al., 2001). A series of submarine canyons with steep eroded walls head at about the 500 m contour. Many intercanyon ridges show almost continuous Quaternary sedimentation. Canyon floors are filled with debris-flow deposits, some sand and gravel beds, and a veneer of Holocene mud.

Regional stratigraphic setting

The Scotian Slope is part of the Mesozoic rifted margin of the central North Atlantic Ocean, with thick Jurassic and Cretaceous strata overlying Triassic salt (Wade and Maclean, 1990). Through the Tertiary, the Scotian margin accumulated prodeltaic shale and was deeply incised by canyons during major sea-level lowstands. In the later Miocene, sediment distribution on the margin was influenced by the Western Boundary Undercurrent. With the onset of terrestrial glaciation during the Pliocene, rapid sedimentation occurred on the Laurentian Fan and on areas of the Scotian Slope. Widespread gullying took place in the early Pleistocene, but the overall style of sedimentation continued to be prodeltaic. Detrital palynomorphs in a core of pelagic sediment from south of the Grand Banks suggest that the first major shelf-crossing glaciation that excavated Carboniferous rocks from the Laurentian Channel occurred about 0.5 Ma in marine isotope stage 12 (Piper et al., 1994). Since that time, the continental slope has been dominated by proglacial sedimentation, with little sediment accumulation during interstades.

Sedimentation during the last glacial cycle

The style of sedimentation during the last glacial cycle is a guide to sedimentation during earlier glacial advances. In the area immediately west of Verrill Canyon, Mosher et al. (1989) showed that the youngest till tongue corresponded approximately to the last glacial maximum at 18 ka. (All ages younger than 40 ka are given in radiocarbon years; all cited C^{14} age determinations are in radiocarbon years with a -0.4 ka marine reservoir correction.) This interpretation has been substantiated by additional radiocarbon dating of sediments that underlie the youngest till tongue horizon (Campbell, 2000; Piper, 2001). In the same area, Gauley (2001) regionally correlated seismic reflectors corresponding to the next two till tongues beneath the youngest till tongue. She used sedimentation rates and correlation with the ice-flow stages

of Stea et al. (1998) to argue that these till tongues corresponded to glacial advances in marine isotope stage 4 (corresponding to the Caledonia phase of Stea et al., 1998) and marine isotope stage 6 (Illinoian Glaciation).

Studies of piston cores by Hill (1984), Mosher et al. (1994), Piper and Skene (1998), and Campbell (2000) show that hemipelagic middle to late Holocene slope sediment comprises bioturbated olive-grey mud, with silty sands at <600 m. Early Holocene and latest Pleistocene olive-grey sediment contains scattered ice-rafted granules and is sandier, including sandy turbidites in deeper water. This olive-grey sediment passes down into brownish and greyish sandy mud and brownish muds with granules, which in turn overlie widespread red-brown clayey turbidites, in places with intercalated sands. These facies are interpreted as ice-margin plume fallout (brown muds with granules) and turbidites (graded sands and interbedded muds) derived from ice that crossed the Scotian Shelf. Distinctive brick-red sandy mud beds occur within the sandy olive-grey sediment and the underlying brownish and greyish mud; they are interpreted as resulting from rapid ice-rafted transport from the Gulf of St. Lawrence between 14 ka and 10 ka (Piper and Skene, 1998). The lowest such bed is commonly overlain by a light tan sandy mud bed correlated with Heinrich event 1 in the Labrador Sea, interpreted as derived from ice-rafting from Hudson Strait. Heinrich event 2 (21 ka) is recognized as a tan bed on the Laurentian Fan (Piper et al., 1999b).

METHODS

Conventional two-dimensional, single-channel seismic reflection data were acquired with one or two Haliburton 40 in.^{3} (0.7 L) sleeve gun(s), the centre frequency of which is about 200 Hz. The system was towed about 1 m below surface. Signals from this source were received on a GSCA designed array manufactured by Benthos. The array has a 25 ft. (7.6 m) lead section comprising 15 AQ-1 hydrophone cartridges at 1.5 ft. (0.5 m) spacing, and a 75 ft. (22.9 m) tail section, comprising 25 cartridges with 3 ft. (0.9 m) spacing. Penetration is typically about 1 s. Older multichannel seismic-reflection data acquired with a 40 in.^{3} sleeve gun source (Piper et al., 1987) have also been used in this study.

High-resolution boomer and sparker profiles were collected with the Huntec DTS system, which is generally towed about 100 m below the sea surface and is heave and depth compensated. Seismic signals were received on a 15 ft. (4.6 m) long, 10-element oil-filled streamer (Benthos MESH 15/10P) towed behind the fish. Signals were filtered at 500 to 5000 Hz with spreading loss gain recovery. The source was operated at 500 J output. The signal contains a broad frequency bandwidth (up to 6 kHz), which yields an optimal vertical resolution of about 0.25 m. Signal levels are generally sufficient to yield acoustic imaging up to 100 m below the seafloor. Horizontal resolution is affected negatively by large water depths and steep topography.

SEISMIC STRATIGRAPHY

On the outermost continental shelf and upper slope, seismic reflection profiles show a series of stacked, acoustically amorphous units separated by high-amplitude, coherent, subplanar reflectors (Fig. 2). It is difficult to determine the total number of stacked amorphous units because units are commonly thin, may be cut out by erosion, and are obscured by seismic artefacts: at least five units are visible in Figure 2. The base of this stacked section is a significant unconformity

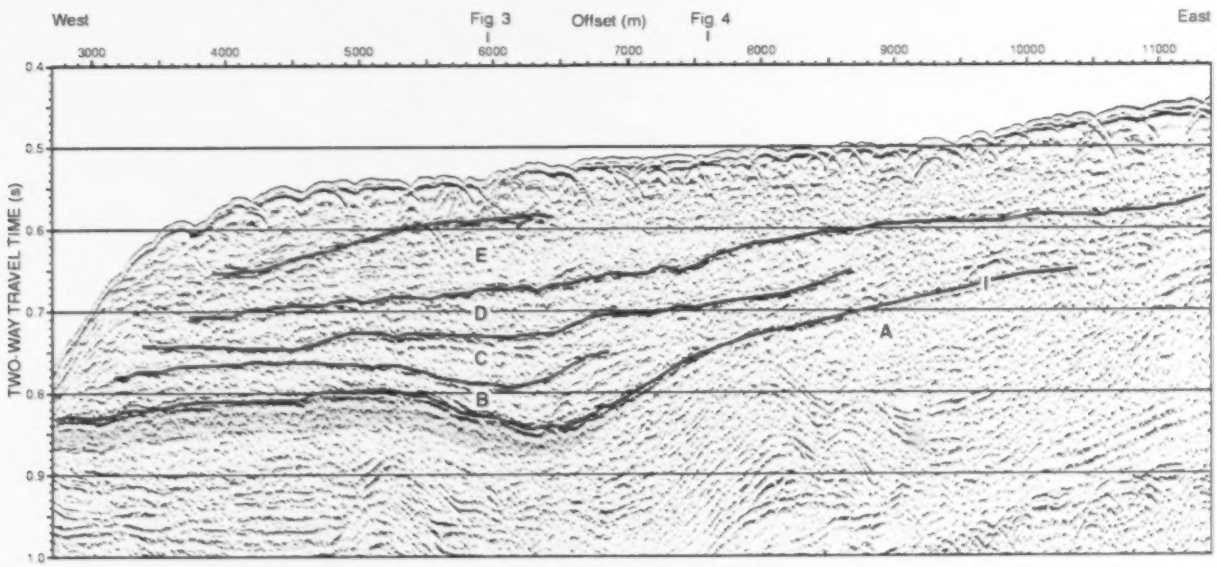

Figure 2. *Strike seismic profile on the upper slope showing stacked till units A to E. Reflector I can be traced regionally and is underlain seaward by an acoustically transparent unit.*

(Fig. 2), which created regional high-amplitude reflector I that overlies the deepest incoherent unit and can be correlated throughout the study area.

The acoustically incoherent units are commonly truncated by the erosional heads of canyons in the downdip direction (Fig. 2). On intercanyon ridges, however, they pass downslope in a complex manner into stratified sediments, with reflector continuity broken locally by erosional features that are probably related to tributary gullies that fed the canyons. It is difficult to recognize till tongues of the type illustrated by Mosher et al. (1989) west of Verrill Canyon because of canyon head erosion, although at least three till tongues are visible in Figure 3 and perhaps as many as six in Figure 4.

The crests of the intercanyon ridges show a reasonably continuous stratigraphic section (Fig. 3), but a strike seismic section just upslope from the heads of the modern canyons shows a complex stratigraphy with numerous episodes of cut and fill (Fig. 5). The section appears to be entirely downslope from the limit of the stacked acoustically incoherent units, although correlation can be made to the till tongues in Figure 4. Several regional unconformities are recognized in this section (Fig. 5), with the shallowest corresponding closely to the present seafloor. Deeper regional unconformities are identified as reflectors I to IV (Fig. 5). Overlying the regional unconformities, small gullies have fills of acoustically incoherent and transparent material interpreted as muddy mass-transport ('debris-flow') deposits by analogy with similar surface deposits on St. Pierre slope (Piper et al., 1999a). At a similar stratigraphic level, the flanks of small gullies show erosional cuts that are interpreted as failure scarps. At least two stratigraphic intervals, one just below the seabed unconformity and one immediately underlying the I marker, show acoustically transparent intervals with very low-amplitude parallel seismic reflections that drape pre-existing topography. This facies is also locally developed beneath the IV marker. A similar draping facies, with higher amplitude reflections, occurs at other stratigraphic levels.

Huntec DTS sparker profiles from intercanyon ridge crests on the lower continental slope show a regionally correlatable succession of high-amplitude reflections alternating with more transparent intervals (Fig. 6). These seismic facies are noted on corresponding airgun profiles.

The acoustic style below reflection I is different from the shallower stratigraphy. In mid-slope dip lines (e.g. Fig. 7), draping over subsurface erosion surfaces is more prominent above reflector I and small erosional scarps are abundant compared to the underlying section. Strike lines on the middle slope show gully cut-and-fill in different positions at different stratigraphic levels above reflector I. Sediment draping tends to have reduced the relief of intergully highs ('mounds'), although locally erosional scarps (2, 3, Fig. 8) enhance it. Below reflector I, canyons or gullies have maintained their position through time and intergully highs have developed a progressively more mounded geometry from an initial almost planar surface at about 1.4 s (Fig. 5). On the other hand, depositional styles are more similar above and below reflector I on the lower slope (Fig. 6).

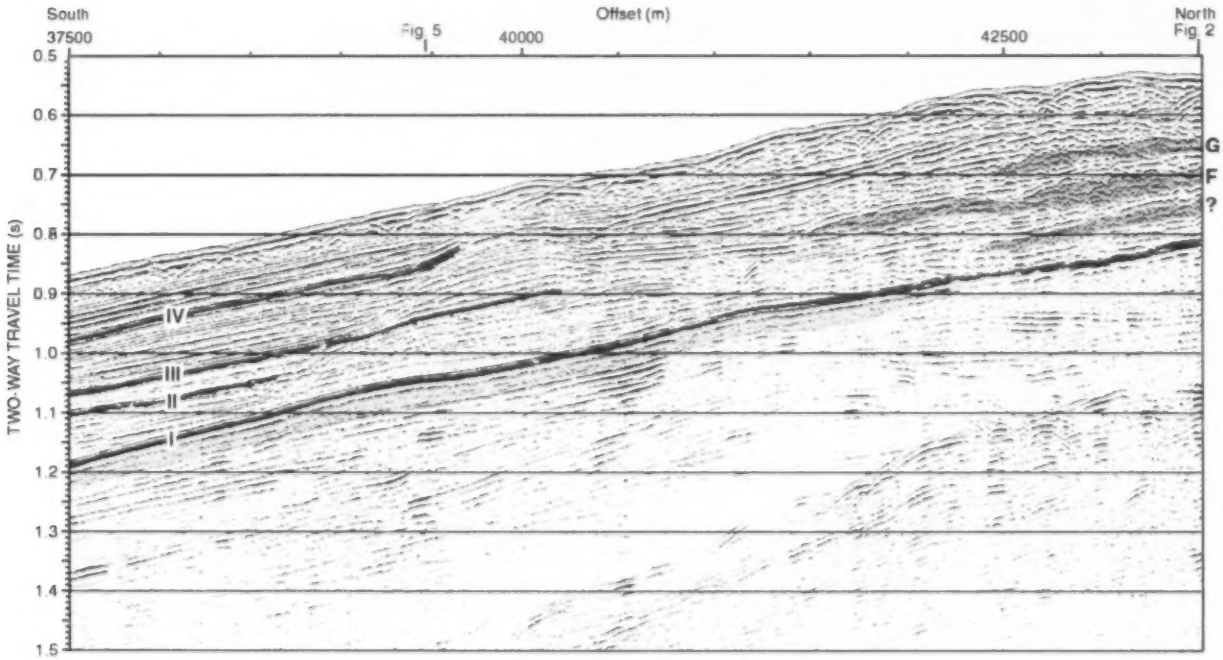

Figure 3. *Dip line from upper slope to intercanyon ridge crest showing stacked till tongues G, F, and a deeper unit, and regional reflectors I through IV.*

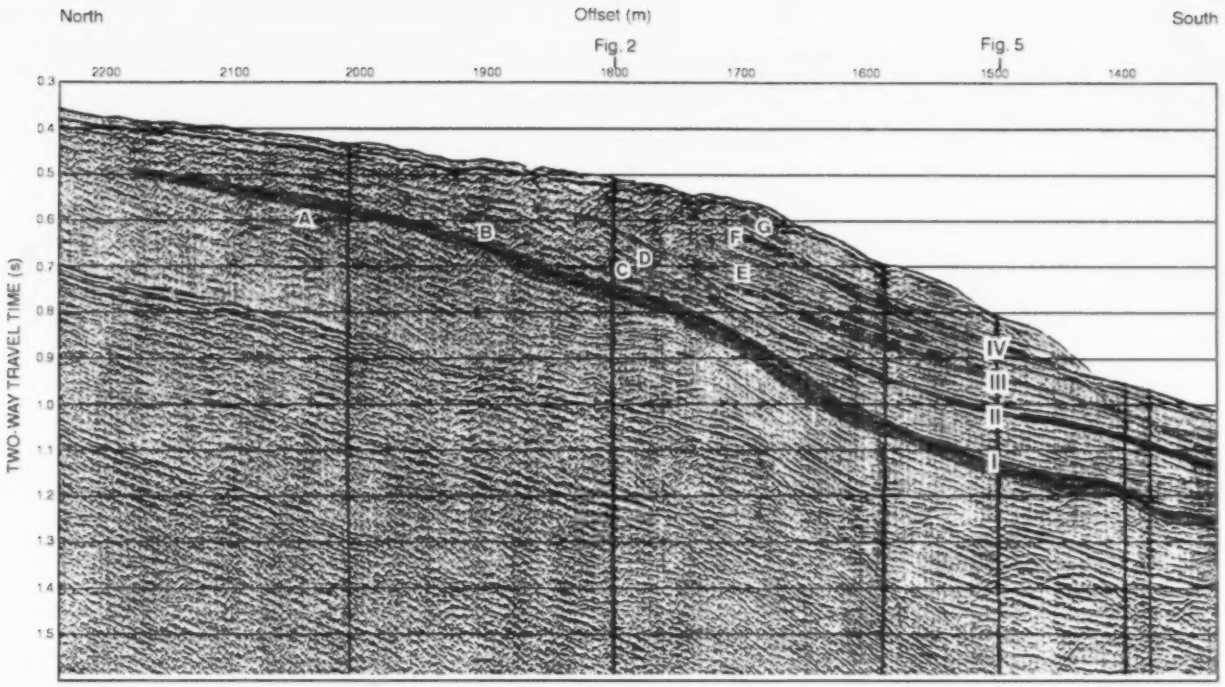

Figure 4. *Dip line showing relationship of stacked tills tongues A to G with regional reflectors I through IV.*

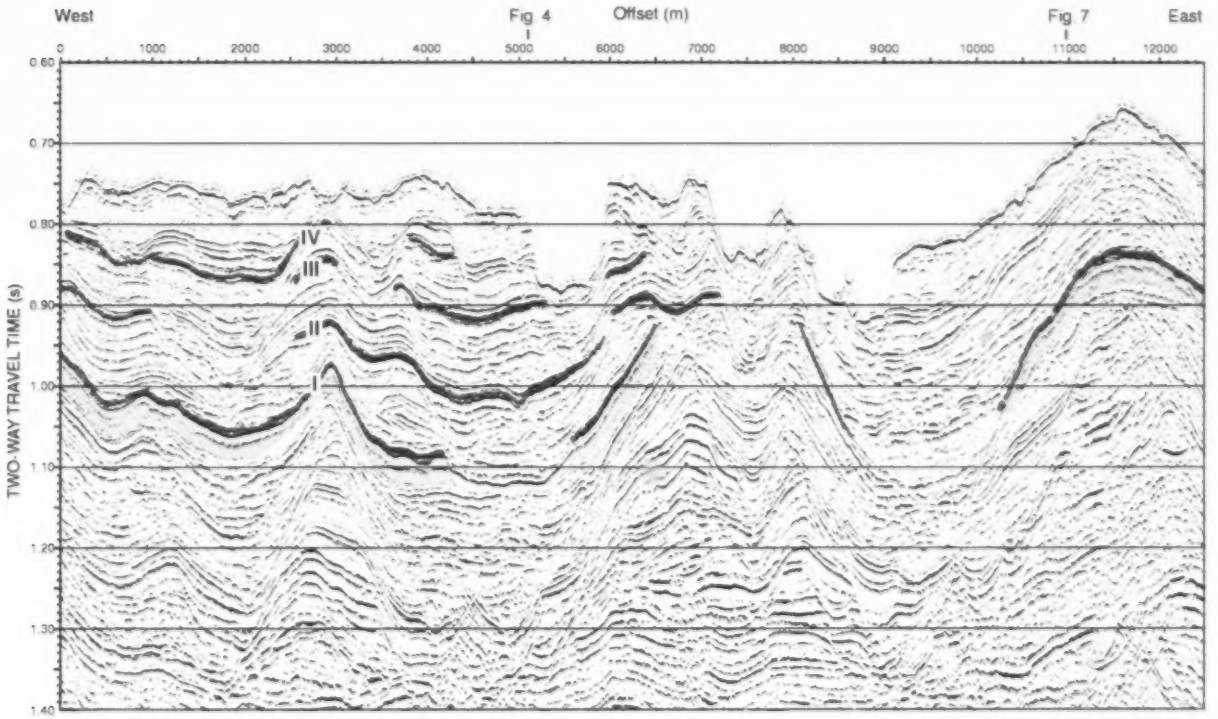

Figure 5. *Strike line (migrated) near the canyon heads showing regional reflectors I through IV.*

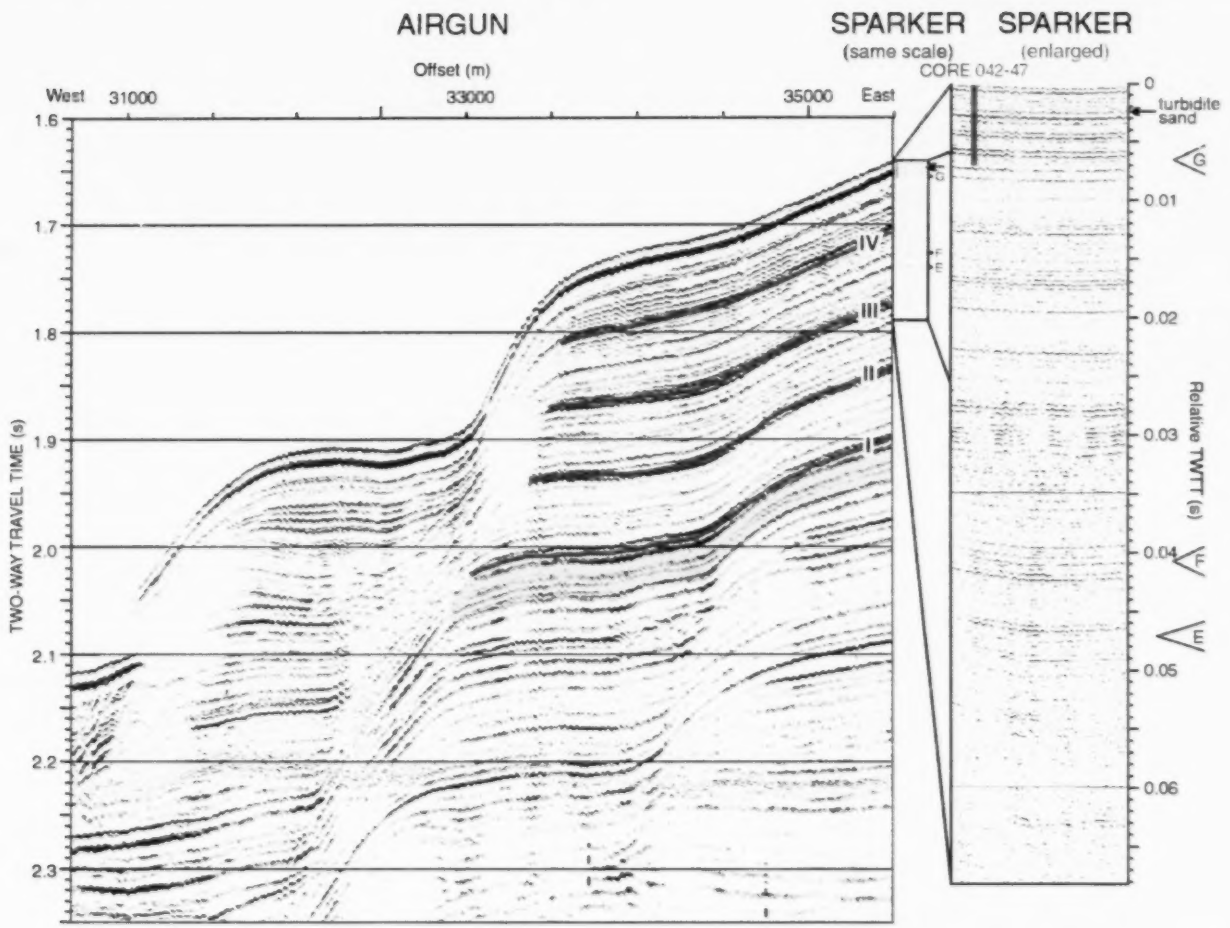

Figure 6. *Airgun and sparker profiles from ridge crest. Also shown is correlation of the sparker profile on reflector character to the dated succession west of Dawson Canyon studied by Gauley (2001) and a nearby core that penetrated approximately to the last glacial maximum. E, F, and G are the approximate positions of till tongues correlated with the section of Gauley (2001).*

INTERPRETATION OF SEISMIC STRATIGRAPHY

Interpretation of acoustic facies

The stacked units of acoustically incoherent material are interpreted as glacial tills, by analogy with similar sequences on the Norwegian Shelf (King et al., 1991) and elsewhere. The evidence of stacked till units on the outer shelf and till tongues beneath the upper slope suggests that there were perhaps as many as six distinct ice advances (Fig. 4). We interpret the tongue-like deposits on the upper slope as overconsolidated till, rather than mass-transport deposits (e.g. Stravers and Powell, 1997), for several reasons. 1) Numerous attempts to core the deposits have failed, yet coring into iceberg-turbated proglacial sediment and mass-transport deposits is generally successful. 2) The seabed overlying the units has numerous iceberg pits, but few linear scours (Pickrill et al., 2001), which is interpreted as evidence of a highly resistant seabed (G. Fader, pers. comm., 2002). 3) Locally, mass-transport deposits have been seen downslope from till tongues and show a more transparent acoustic character (Bonifay and Piper, 1988).

Correlation of the succession of acoustic facies in Figure 5 with the till tongues in Figure 4 shows that the major erosion surfaces recognized as regional reflectors lie a short distance below the tips of till tongues. A packet of one or more conformable high-amplitude reflections overlies these regional reflectors (Fig. 8). This packet tends to be thicker in depressions and less evident on highs. It is overlain by acoustically incoherent material filling depressions. The tips of the till tongues appear to be at the same stratigraphic level as the base

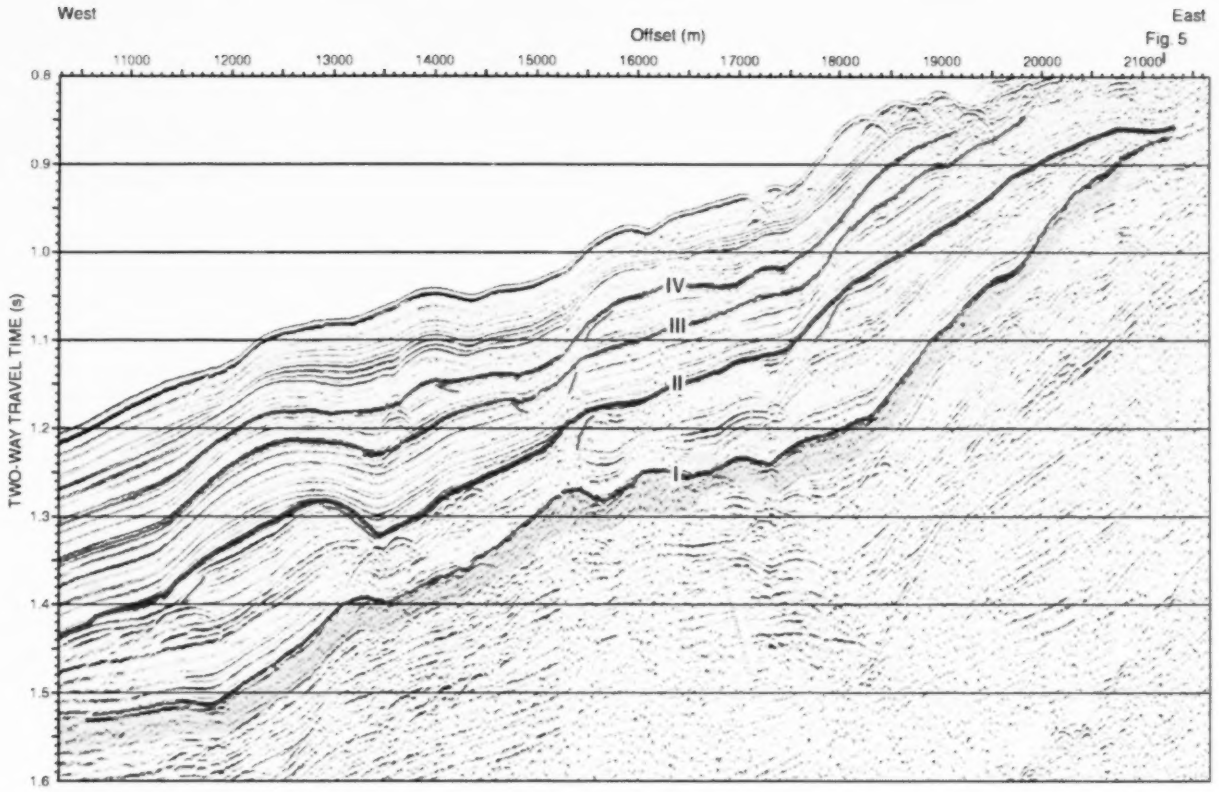

Figure 7. *Dip line showing stratified proglacial sediments cut by numerous failure scarps.*

of the acoustically incoherent units. These sequences are interpreted as possible erosional events related to till-tongue deposition with associated deposition of mass-transport deposits and subsequent glaciomarine sediments deposited as turbidites and hemipelagites.

The transparent drape beneath reflector I has the same acoustic character as sediment 1 to 2 m below the modern seafloor (e.g. Fig. 5). These near-surface sediments consist of uniform proglacial mud with scattered ice-rafted detritus, as seen in piston cores. This mud includes distinctive red mud beds that thicken eastward and appear to have a source from the Gulf of St. Lawrence. The sediment beneath reflector I is interpreted to have a similar origin, from its similar acoustic character. In the 1 Ma pelagic sediment succession in core 87008-003 from the J-Anomaly ridge, marine isotope stage 12 is marked by a remarkable thickness of red clays derived from the Gulf of St. Lawrence, presumably from a proglacial plume or mid-water nepheloid layer. No other glacial interval has a similar deposit. This observation supports the interpretation that reflector I dates from marine isotope stage 12.

Several processes might account for the regional unconformity surfaces such as reflectors IV and III. To within the resolution of the seismic reflection profiles, they appear to correspond to the base of the till bodies on the outer shelf, but are 10 to 20 ms below the tips of the till tongues. Thus the high-amplitude reflections, tending to be thicker in depressions, might correspond to either interglacial conditions with sandy sediment derived from storm reworking of the outer shelf (Hill and Bowen, 1983), or sandy proglacial deposition as ice sheets advanced. The unconformities themselves include both horizontal erosional surfaces (1, Fig. 8) and steep erosional walls, either remote from gullies (2, Fig. 8) or at their margins (3, Fig. 8). The fact that erosion is not restricted to gullies suggests that sediment failure is a more likely mechanism than erosion by hyperpycnal meltwater or turbidity currents. No evidence was found for erosion by glacial ice, and only at the modern seafloor was water depth sufficiently shallow for iceberg scouring. Analogy with the seabed unconformity suggests that the unconformities are created by failure of rapidly deposited proglacial sediment as a result of seismicity triggered by rapid glacial unloading. This interpretation is consistent with reflector I unconformity overlying the thick plume deposits of marine isotope stage 12. The overlying sediments, which return a high-amplitude reflection even from topographic highs (e.g. clearly seen above reflector II in Fig. 8), are analogous to reflections returned by deglacial ice-rafted horizons such as the brick-red

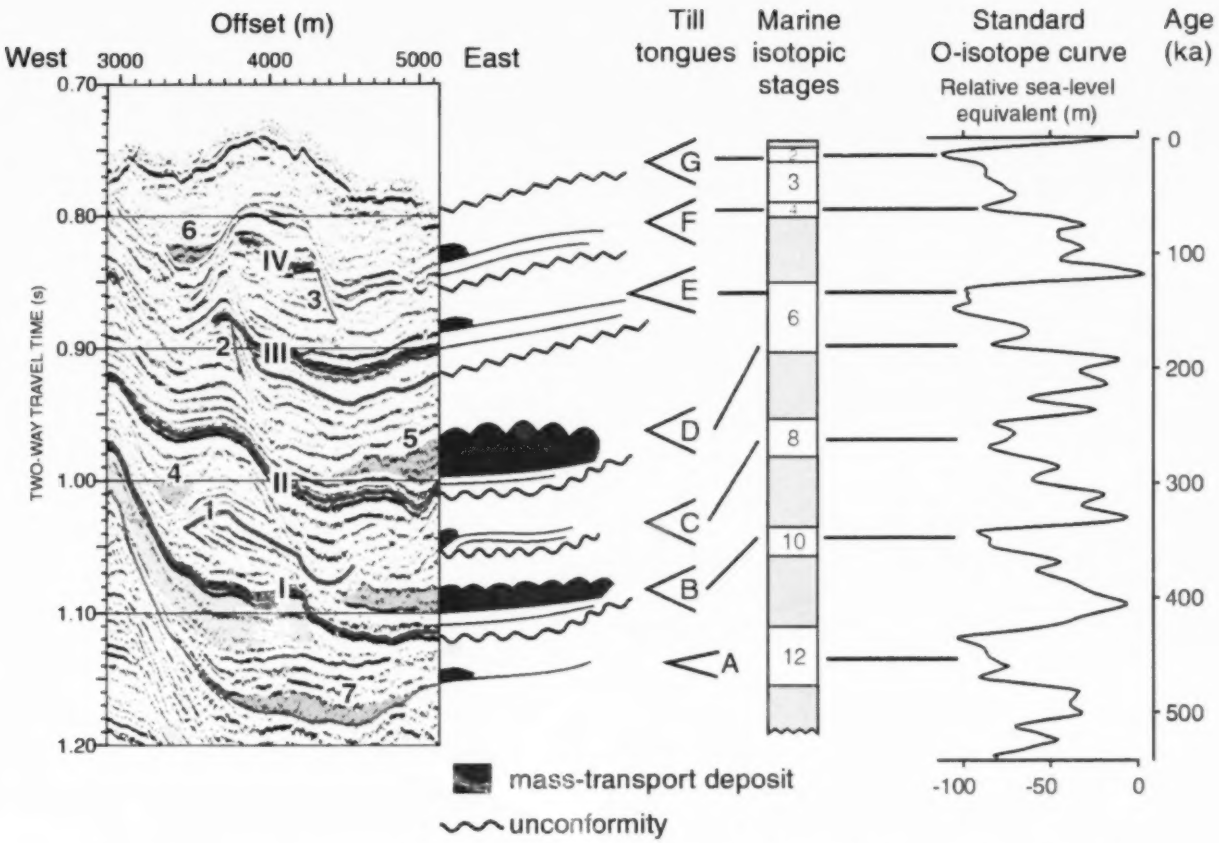

Figure 8. *Cartoon interpretation of the relationship of upper slope sedimentation to glacial cycles. The seismic profile is part of Figure 5. For explanation of 1 through 7 on the seismic profile, see text.*

mud units described by Piper and Skene (1998), which consistently give a high-amplitude seismic return (e.g. Piper et al., 1999b, Fig. 4). In addition, seabed winnowing by bottom currents results in sandy interglacial sediments in water depths of less than 1000 m (Piper and Campbell, 2002).

Acoustically incoherent deposits that fill depressions and have rough upper surfaces (Fig. 8) are interpreted as mass-transport deposits. Core studies show that mass-transport deposits are widespread immediately following the last glacial maximum. It is unclear whether they were triggered directly by glacier advance, as suggested by the data of Gauley (2001), or whether they resulted from seismically triggered failure. Most are overlain by draped, relatively transparent sediment packets (e.g. 4, 5, 6, Fig. 8), suggesting that they are glacial maximum deposits, developed downslope from an ice margin in the same manner as mass-transport deposits downslope from the youngest till tongue on St. Pierre slope (Bonifay and Piper, 1988, Fig. 5).

The acoustically transparent unit beneath reflector I, interpreted as plume deposits, can be traced laterally into broad channel deposits (7, Fig. 8). The base of the plume deposits corresponds to a mass-transport deposit, which is overlain by onlapping high-amplitude reflections, interpreted as turbidites by analogy with late Wisconsinan mass-transport deposits (Piper and Shor, 1990). Similar channel-floor deposits occur at several underlying stratigraphic horizons.

The change in acoustic style at about reflector I is similar to that previously noted by Piper and Normark (1989) and Mosher et al. (1989) as corresponding to the base of the till tongue sequence and thus marking a change from prodeltaic to proglacial sedimentation. This change in style is most pronounced on the middle slope. On the lower slope, the similarity of sedimentation above and below reflector I may reflect the greater role of turbidity currents as a depositional process at this water depth.

Age of the stratigraphic section

Direct evidence for the age of the stratigraphic section is restricted to radiocarbon dating of cores from west of Verrill Canyon (Campbell, 2000; Gauley, 2001). There, a prominent regional reflector, purple, is at a subbottom depth of 35 ms at 900 mbsl and 25 ms at 1200 mbsl. The age of purple is estimated to be about 30 ka and is constrained by an underlying

radiocarbon age of 36.4 ka and an overlying age of 23.3 ka. Upslope, much of the section above purple appears to be ice-proximal. Sedimentation rates are much lower in the 14 ka to present interval, when ice was absent from the outer shelf. Extrapolation of sedimentation rates to deeper reflectors thus depends on whether proglacial or nonglacial conditions prevailed on the outer shelf. Gauley (2001), working west of Verrill Canyon, argued that a deeper till tongue at about 1.6 times the subbottom depth of purple likely represents an early Wisconsinan advance. It corresponds to the Caledonia advance of Stea et al. (1998), when New Brunswick ice flowed southeastward across the Bay of Fundy and mainland Nova Scotia.

Constraints on the age of the oldest shelf-crossing glaciation are equally tenuous. On land in Nova Scotia, there is no evidence for glaciation older than Illinoian (marine isotope stage 6) (R. Stea, pers. comm., 2002). From the detrital record on the J-Anomaly ridge, major erosion of the Laurentian Channel first took place during marine isotope stage 12, although the first shelf-crossing glaciation out of the Gulf of St. Lawrence might have been as early as marine isotope stage 16 (Piper et al., 1994). At ODP site 1063 on the Bermuda Rise, sedimentation rates of sediment derived largely from glaciation of Atlantic Canada were higher from marine isotope stages 6 to 2 than from marine isotope stages 7 to 16 (Giosan, 2001).

Correlation of acoustic stratigraphy with global ice-volume proxy

The global marine oxygen isotope record is a proxy for global ice volume (Fig. 8). Ice extent off Nova Scotia can be expected to reasonably parallel global ice volume. We use the observation that till tongue E is of unusually great extent to attempt a correlation with the global ice-volume proxy. We explore the possibility that this till tongue represents the Illinoian Glaciation of marine isotope stage 6, one of the most extensive Pleistocene glaciations known. The two overlying till tongues, G and F, would then correlate with marine isotope stages 2 and 4. The subbottom depth of reflector IV, corresponding to till tongue F, is 100 ms at 900 mbsl (Fig. 7). Linear extrapolation of sedimentation rates from the age of the purple reflector west of Verrill Canyon would give an age of about 90 ka; however, with a long period of nonglacial sedimentation in marine isotope stage 5, an age of 130 ka for reflector IV implied by this correlation seems quite reasonable. In Figure 7, reflector I is at three times the subbottom depth of reflector IV. Linear extrapolation of ages would give an age of about 400 ka, suggesting that reflector I could reasonably date from about marine isotope stage 12 (450 ka). This is consistent with the observation of thick plume deposits immediately below reflector I, which are correlated with the only occurrence of red clays in the long pelagic section in core 87008-003 from the J-Anomaly ridge.

The interpretation of the succession of till tongues is that till A corresponds to marine isotope stage 12 and at the same time major deposition of proglacial sediment took place on the continental slope. Reflector I marks the change to interglacial sediments of marine isotope stage 11. Overlying till tongues B and C most reasonably date from marine isotope stages 10 and 8, respectively. Marine isotope stage 6 shows two heavy peaks in the oxygen isotope record, analogous to those of marine isotope stages 4 and 2. We correlate till tongue D with the older of these two glacial stades in marine isotope stage 6. The base of till tongue E is a major erosion surface on the outer shelf and upper slope and E extends farther downslope than any other till tongue; it is interpreted to date from the extreme glaciation at the end of marine isotope stage 6. Smaller near-surface till tongues F and G date from marine isotope stages 4 and 2. The thick draped sediments overlying mass-transport deposits are thickest between marine isotope stages 6.3 and 6.1 and marine isotope stages 4 and 2, the latter being a time when ice is unlikely to have retreated from land areas of Nova Scotia (R. Stea, pers. comm., 2002). Mean sedimentation rates implied by this chronology are substantially higher from marine isotope stage 6 to the present, compared to marine isotope stages 7 to 11. This is consistent with the evidence of rates of sediment supply on the Bermuda Rise (Giosan, 2001).

We have considered and rejected other possible correlations of till tongues with marine isotope stage stratigraphy. Adopting the argument proposed by R. Stea (pers. comm., 2002) that because pre-Illinoian deposits are not known on land in Nova Scotia, the first shelf-crossing glaciation was in marine isotope stage 6, would imply proglacial sedimentation rates much higher than those known in the past 36 ka. A more tenable hypothesis is that the first shelf-crossing glaciation represents a horizon as old as marine isotope stage 16 or 22 (both times of high global ice volume), so that till tongue B or C might represent marine isotope stage 12 and the marine isotope stage 10 glacial advance would not be represented in the till tongue stratigraphy. This possibility cannot be excluded, although it implies proglacial sedimentation rates much lower than those of the late Wisconsinan. Neither does it account for the thick inferred plume deposit immediately below reflector I.

CONCLUSIONS

Seismic facies in the upper few hundred milliseconds on the middle Scotian Slope can be interpreted in terms of near-seabed facies known from high-resolution seismic reflection profiles and piston cores. A series of stacked till tongues is recognized on the upper slope, and their downslope pinchouts are interpreted to represent glacial maximum conditions. The deepest till unit immediately underlies regional reflector I, which marks a change in depositional style on the continental slope. Regional unconformities appear to represent sediment failure immediately following deglaciation and reworking of sediment on highs by currents. Gullies contain mass-transport deposits that correspond to glacial maxima. Thick glacial-plume deposits are characteristic of the last deglacial period, and acoustically similar deposits are recognized above some deeper till tongues. Such deposits are most prominent beneath regional reflector I and are correlated with

thick plume deposits derived from the Gulf of St. and Lawrence known to have occurred during marine isotope stage 12 from a long pelagic core from the J-Anomaly ridge. This chronological correlation allows consistent interpretation of the ages of till tongues on the upper slope and of proglacial facies on the middle slope. The till tongue that extended farthest seaward formed at the end of marine isotope stage 6. Till deposits in marine isotope stage 12 are recognized only on the outermost shelf and did not extend to the slope. Prior to marine isotope stage 12, prodeltaic sedimentation predominated on the upper and middle slope.

ACKNOWLEGMENTS

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